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WITNESS my hand this
Seventeenth day of November 2003

JANENE PEISKER
TEAM LEADER EXAMINATION
SUPPORT AND SALES

AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

Applicant(s):

UNIVERSITY OF TECHNOLOGY, SYDNEY

Invention Title:

A LIGHT COLLECTOR

The invention is described in the following statement:

A LIGHT COLLECTOR

Field of the Invention

The present invention broadly relates to a light collector for use in a fluorescent daylight collection and light transport system and to a method of designing the light collector.

Background of the Invention

Electrical lighting systems are often very inefficient; usually more than 90% of the electrical energy is not converted into useful light. Sunlight, however, is freely available and attempts have been made to collect sunlight for illumination purposes.

US Patent 6059438 discloses a sunlight collecting and transmitting system. The disclosed system comprises three substantially flat collector sheets. The three sheets are stacked on top of each other and are composed of a polymeric material that is doped with fluorescent dye molecules. The dye molecules absorb sunlight of a particular wavelength and subsequently emit fluorescent light having a slightly longer wavelength. A first sheet is doped with blue dye molecules, a second sheet is doped with green dye molecules and a third sheet is doped with red dye molecules. The generated fluorescent light is guided by internal reflection within the collector sheets and white light can be generated by combining the blue, green and red fluorescent light. One of the advantages of this sunlight collecting and transmitting system is that the emission of the fluorescent light does not occur in any preferred directions while the absorption is only weakly sensitive to the distribution of incident rays at any one time. That is the collector responds well to both

diffuse and beam or specular solar radiation. Focussing concentrators in contrast give almost no useful output under diffuse partially cloudy skies. The efficiency of this system depends largely on the total solar flux falling on the collector modified only slightly according to the average incident direction of the incoming sunlight.

However, the intensity of the generated fluorescent light that is emitted at any edge does not increase in direct proportion to the increase in solar energy incident on the light collector as a result of increase in its area since a larger collector requires more fluorescently emitted light to travel further before exit from the collector and so there is a greater chance it will be lost, due to various loss processes that occur in practice. The dye molecules may introduce defects in the matrix of the material that forms the light collector. These defects result in optical scattering of light and the resultant intensity losses increases with the distance light travels. Further, losses occur due to re-absorption of emitted light.

In general, loss mechanism in the light collector sheet my be divided into two components: loss mechanism "m" relates to losses that guided light will suffer due to attenuation owing to scattering at structural defects of the matrix material in which the dye molecules are dispersed and loss mechanism "d" involves scattering and re-absorption at the dispersed dye-molecules themselves. Losses that guided light will suffer may be quantfyed by the attenuation half length h_m and h_d which are the distances at which the intensity of fluorescent light emitted at a first position is reduced by 50% owing to the respective losses. A third attenuation half length h_{m+d} is

defined as the distance at which the intensity of fluorescent light emitted at a first position is reduced by 50% owing to both losses mechanisms.

Summary of the Invention

The present invention provides a light collector having a concentration of dye molecules that are dispersed in a light transmissive medium, the concentration being selected to reduce attenuation that light will suffer due to re-absorption or scattering in the main emission wavelength range of the dye molecules so that the combined emission and absorption efficiency of the light collector is increased.

The light collector has a dye concentration that may be between 120 and 100ppm, between 100 and 80ppm, between 80 and 60ppm, between 60 and 40ppm, between 40 and 20ppm, between 20 and 10ppm or less than 10 ppm.

The light collector preferably has a dye concentration that is selected such that attenuation which light will suffer due to re-absorption or scattering in the main emission wavelength range is minimised. The light collector most preferably has a dye concentration that is selected such that attenuation that light will suffer due to re-absorption or scattering in the main emission wavelength range is minimised and the combined emission and absorption efficiency of the light collector is optimised.

Using high quality light collectors having a very low density of defects, the inventors made the surprising discovery that the spectral range in which dye concentration linked loss occurs extends into the main emission band. The inventors have also discovered that,

if this extended loss tail which is linked to the presence of dye is taken into account, the dye concentration can be optimised and the increase in efficiency is significant in systems of useful dimensions. The optimum dye concentration is lower than previously predicted and the efficiency of light collectors having such dye concentration is significantly improved compared with light collectors that were designed using a method that does not take into account the extension of the weak loss tail into the main emission range.

The dye molecules preferably are distributed such that at least a majority of the dye molecules are not directly bonded to one another. The dye molecules preferably are not directly bonded to one another and most preferably are substantially uniformly distributed throughout the light collector.

The present invention also provides a method of designing a light collector being doped with dye molecules that, in use, absorb light having a wavelength within an absorption wavelength range and emit light having a wavelength within an emission wavelength range, the method comprising the step of calculating a concentration of the dye molecules taking into account the attenuation that emitted light will suffer owing to re-absorption or scattering in the main emission wavelength range.

The present invention further provides a light collector designed by the above-defined method.

The present invention even further provides a method of fabricating the light collector designed by the above-defined method.

The above-defined method preferably comprises the step of selecting the dimensions of the light collector

and calculating the dye concentration for the selected dimensions. The step of calculating the dye concentration may also take into account reflection properties of a medium that will be positioned adjacent the light collector.

The wavelength range in which attenuation owing to re-absorption or dye related scattering is taken into account preferably extends beyond a wavelength that corresponds to maximum emission intensity. The wavelength range for which attenuation is taken into account most preferably extends to a wavelength about 80 nm longer than the wavelength that corresponds to maximum emission intensity. For this calculation attenuation preferably is considered and measured at levels of down to 1 part in 10^4 in standard thicknesses for transmittance of a few mm or equivalently specular transmittance (apart from usual reduction due to smooth surface reflectance) and most preferably is not approximated by 100% until it is above 99.99%.

The wavelength range in which attenuation owing to re-absorption or weak scattering is taken into account may be from 380 nm to 480 nm for light collector doped with dye molecules that, in use, emit violet fluorescent light. For a light collector that is doped with dye molecules that, in use, emit green fluorescence radiation the wavelength range in which attenuation owing to re-absorption or weak scattering is taken into account may be from 460 to 700 nm. For a light collector that is doped with dye molecules that, in use, emit red fluorescence radiation the wavelength range in which attenuation owing to re-absorption is taken into account may be from 530 nm to 750 nm.

The step of calculating the dye concentration preferably is conducted such that a dye concentration for optimum combined absorption and emission efficiency is obtained.

Brief Description of the Drawings

Figure 1 shows a light collector according to an embodiment of the present invention and

Figure 2 shows a transmission versus wavelength plot for a light collector designed according another preferred embodiment of the invention.

Detailed Description of Preferred Embodiments

A method of designing a light collector according to a preferred embodiment of the present invention is now described. In general, the method concerns the design of a light collector of the type shown in Figure 1. The light collector 10 is doped with dye molecules that, in use, absorb light 12 having a wavelength within an absorption wavelength range and emit light 14 having a wavelength within an emission wavelength range. The method of designing the light collector 10 comprises the step of calculating an optimum concentration of the dye molecules taking into account the attenuation that emitted light will suffer owing to re-absorption or scattering in a wavelength range that extends across much or all of the emission wavelength range.

Initially the absorption or extinction coefficient $A(\lambda)$ directly attributable to dye molecules at a known concentration x (x is in units of either wt% or dye molecules per unit volume) is measured from optical specular transmittance measurements at known thickness and concentration x in the host material which is known to

have negligible scattering at the thicknesses used. For any concentration x_c, a coefficient $\alpha(\lambda)$ can be estimated from $\alpha(\lambda) = A(\lambda)(x_c/x)$. It is the dye concentration x_c which is optimised. The coefficient $\alpha(\lambda)$ is almost exclusively dependent on the dye absorption process which leads to fluorescence, but at long wavelengths λ, where it is relatively very weak and hence difficult to measure accurately in standard set ups, other dye induced loss processes may occur and make up a significant component of $\alpha(\lambda)$, if it is non zero at these wavelengths. [Though weak these long wavelength losses linked to dye concentration can have a very significant impact on output in these systems. Data on complete systems indicates their importance.]

For these measurements it is important that the dye molecules are dispersed fully, that is at a monomolecular level. High accuracy in transmittance data is very important in the region where the absorption spectrum overlaps the fluorescence emission spectrum, especially where loss is small and relatively negligible in thin samples. Measurements through thicker samples or even along the length inside a long sheet are ideal but need special instrumentation and light sources.

The ideal dye concentration will depend on collector length L and to some extent on width w and thickness t. Thus these design parameters have first to be established.

Output power spectrum at the collection edge of interest is calculated from equation (1) at each dye concentration with $\alpha(\lambda)$ linear in concentration

$$\varepsilon(\lambda,L)=\frac{\varepsilon_o(\lambda)}{\int\varepsilon_o(\lambda')d\lambda'}\frac{E_A}{t(\frac{\pi}{2})}\int_0^L dl\int_\chi^{\pi/2}\sin\phi d\phi\int_0^{a\sin(\frac{\cos\chi}{\sin\phi})}e^{\frac{-(\alpha(\lambda)+\alpha_m)l}{(\sin\phi\cos\theta)}}d\theta \qquad (1)$$

The fluorescent dye has a power spectrum $\varepsilon_o(\lambda)$ (with SI units $W\cdot m^{-2}\cdot nm^{-1}$, and where the subscript "o" denotes the spectrum of emitted radiation prior to encountering other dye molecules). The angles ϕ and θ are standard spherical co-ordinates, χ is the critical angle of the matrix material for total internal reflection and α_m represents any matrix or surface losses which are independent of dye molecules and hence not correlated to dye concentration. It is assumed here to be independent of wavelength. A detailed schematic of this geometry is given in [Swift P.D.,Smith G.B. and Franklin J. (1999) "Light to light efficiencies in Luminescent Solar Concentrators", SPIE Conference on Solar Optical Materials, pp. 21 - 28, Denver, Colorado]. The distance travelled by a particular ray emitted from the dye molecule before it reaches the output edge is $1/\sin\phi\cos\theta$. For the case in which sunlight is distributed uniformly over the top surface of the LSC (with area wL) at normal incidence, the absorbed energy per unit area, E_A, is

$$E_A=\frac{(1-R_c)\int(1-e^{-\alpha(\lambda)l})S(\lambda)\eta_e(\lambda)d\lambda}{wL} \qquad (2)$$

where R_c is the reflectivity of one surface of the collector and η_e the energy-conversion efficiency of the dye. It is not necessary to know E_A explicitly for optimisation of concentration to minimise losses, but it is necessary for total output, since E_A also depends on concentration via $\alpha(\lambda)$.

Finally, the useful power output P (in Watts) for lighting is calculated by summing over all wavelengths taking account of the spectral sensitivity of the eye given by the photopic function $y(\lambda)$. Its equivalence in lumens F, is given by a conversion constant σ, for lighting energy to lumens. The complete formula is:

$$F_{cu} = \sigma \int_{\lambda_{min}}^{\gamma_{max}} dl \int_{0}^{L} \varepsilon(\lambda, L) y(\lambda) d\lambda \qquad (3)$$

F is tabulated or plotted as a function of dye concentration and the optimum concentration is that for which it is maximised.

Dye cost could also be taken into account if desired in determining a final optimum though in general it will be a minor consideration since dye cost forms a very small part of total system cost.

Figure 2 shows a transmission versus wavelength plot (solid line) for a light collector doped with green dye molecules and designed according to the preferred method.

In the following effects of design variations will be considered.

The optimum dye concentration approaches previously used had assumed self absorption, and indeed all dye linked attenuation, had lost their influence after the light had travelled a few cm with further absorption coefficient losses for longer distance measured in attenuation measurements on full sheets, then due to host matrix scattering. Calculation based on this old approach for a green output collector sheet 135x1200x2 mm with output at one 135 mm wide edge, and a sub sheet and one edge reflector, gave optimum concentrations in green

emitting dye around 60 to 70 ppm, while the improved approach lowered this optimum to between 30 and 40 ppm and predicts an increase in total output of up to 1200 lumens.

Variations in the optimum concentration and associated calculation can result from additional or improved design features. The most likely additional influence is that of a strong reflector, either white diffuse or specular metallic, placed beneath the sheet and then an edge reflector at the edge opposite the output edge, as were both used in the above calculation. The under sheet reflector means less dye can be used to obtain the same or higher E_A value since non-absorbed light on the first pass can be largely absorbed after reflection. Less dye also reduces transport losses so the effect of this reflector contributes to improved performance in two ways, and can significantly change the optimum concentration. A simplified approach to the effect of a sub-sheet reflector is to change t in the equation for E_A to 2t. Alternately a fully accurate calculation including the reflectance of the sub-sheet can be made, although in practice this leads to small changes (any wavelength dependence of mirror or sheet reflectance which should be small could also be included or neglected). The edge reflector requires an additional term to the integral in equation (1), in which 1 is relaced by (2L-1), assuming a perfect edge reflector. This terms is also improved for lower attenuation in the emission band, as it requires output light to travel further than in the first term.

The above consideration concerned single sheet calculations. Optimisation of concentration can also be further refined if desired for each different dyed sheet according to its position in a complete collector which will use typically three, or sometimes two dyed sheets, in

a stack. For instance, violet, green and red in that order, with a reflector beneath the whole stack. In this case it is necessary to calculate the power spectra that is impinging on each sheet at each pass (i.e. on way down and way up after reflection), after it has been modified by passing through any sheets above or below. This includes any light not absorbed in prior passes through any sheets and light emitted fluorescently from sheets either side. In this case in equation (2) above for each sheet $S(\lambda)$ is replaced by the incident power spectrum $S_{v,g,}(\lambda)$, with subscript v, g and r, and so on, labels as appropriate for the sheets with different coloured dyes which solar energy has previously passed through, if any. These spectra are determined by multiplying the incident spectrum in the sheet above, by its spectral transmittance. For example after crossing the top violet sheet the spectrum incident on the green below it in a three layer stack is

$$S_v(\lambda) = T_v(\lambda) S(\lambda) \qquad (4)$$

with $T_v(\lambda)$ the spectral transmittance of the violet sheet. Modifications of the incident spectra in this way can change the optimum concentrations but again it is a secondary effect so the first simple approach modified by a base reflector will often suffice, even for a multi-layer, multi-dye system. Flourescent output from above or below can be added . It makes slight changes.

It is to be understood that the reference that is made to US Patent 6059438 and to the publication by Swift et al does not constitute an admission that the documents form a part of the common general knowledge in the art, in Australia or any other country.

Although the invention has been described with reference to particular examples, it will be appreciated by those skilled in the art that the invention may be embodied in many other forms.

The claims defining the Invention are as follows:

1. A light collector having a concentration of dye molecules that are dispersed in a light transmissive medium, the concentration being selected to reduce attenuation that light will suffer due to re-absorption or scattering in the main emission wavelength range of the dye molecules so that the combined emission and absorption efficiency of the light collector is increased.

3. The light collector as claimed in claim 1 wherein the concentration is between 120 and 100 ppm.

3. The light collector as claimed in claim 1 wherein the concentration is between 100 and 80 ppm.

4. The light collector as claimed in claim 1 wherein the concentration is between 80 and 60 ppm.

5. The light collector as claimed in claim 1 wherein the concentration is between 60 and 40 ppm.

6. The light collector as claimed in claim 1 wherein the concentration is between 40 and 20 ppm.

7. The light collector as claimed in claim 1 wherein the concentration is between 20 and 10 ppm.

8. The light collector as claimed in claim 1 wherein the concentration is less than 10 ppm.

9. The light collector as claimed in claim 1 having a dye concentration that is selected such that attenuation which light will suffer due to re-absorption or scattering in the main emission wavelength range is minimised.

10. The light collector as claimed in claim 1 having a dye concentration that is selected such that the combined emission and absorption efficiency of the light collector is optimised.

11. The light collector as claimed in any one of the preceding claims wherein the dye molecules are distributed such that at least a majority of the dye molecules are not directly bonded to one another.

12. The light collector as claimed in any one of the preceding claims wherein the dye molecules are not directly bonded to one another.

13. The light collector as claimed in any one of the preceding claims wherein the dye molecules are substantially uniformly distributed throughout the light collector.

14. The light collector as claimed in claim 1 having a length between 1 and 1.5 m and a dye concentration 30 to 40 ppm.

15. A method of designing a light collector being doped with dye molecules that, in use, absorb light having a wavelength within an absorption wavelength range and emit light having a wavelength within an emission wavelength range, the method comprising the step of calculating a

concentration of the dye molecules taking into account the attenuation that emitted light will suffer owing to re-absorption or scattering in a wavelength range that extends to the main emission wavelength range.

16. The method as claimed in claim 15 comprising the additional step of selecting the dimensions of the light collector and calculating the dye concentration for the selected dimensions.

17. The method as claimed in claim 15 or 16 wherein the step of calculating the dye concentration takes into account reflection properties of a medium that will be positioned adjacent to the light collector.

18. The method as claimed in any one of claims 14 to 16 wherein the wavelength range in which attenuation is taken into account that extends beyond the main emission wavelength range.

19. The method as claimed in any one of claims 15 to 18 wherein the wavelength range for which attenuation that is taken into account that extends to a wavelength about 80nm longer than the wavelength that corresponds to maximum emission intensity.

20. The method as claimed in any one of claims 15 to 19 wherein the wavelength range in which attenuation is taken into account extends from 380 to 480 nm.

21. The method as claimed in any one of claims 15 to 20 wherein the wavelength range in which attenuation is taken into account that extends from 460 to 700 nm.

22. The method as claimed in any one of claims 15 to 21 wherein the wavelength range in which attenuation is taken into account that extends from 530 to 750 nm.

23. The method as claimed in any one of claims 15 to 22 wherein the step of calculating the dye concentration is conducted such that a dye concentration for optimum combined absorption and emission efficiency is obtained.

24. A method of fabricating the light collector designed by the method claimed in any one of claims 15 to 20.

25. A light collector designed by the method claimed in any one of claims 15 to 24.

DATED this 5th day of November 2002
UNIVERSITY OF TECHNOLOGY, SYDNEY
By their Patent Attorneys
GRIFFITH HACK

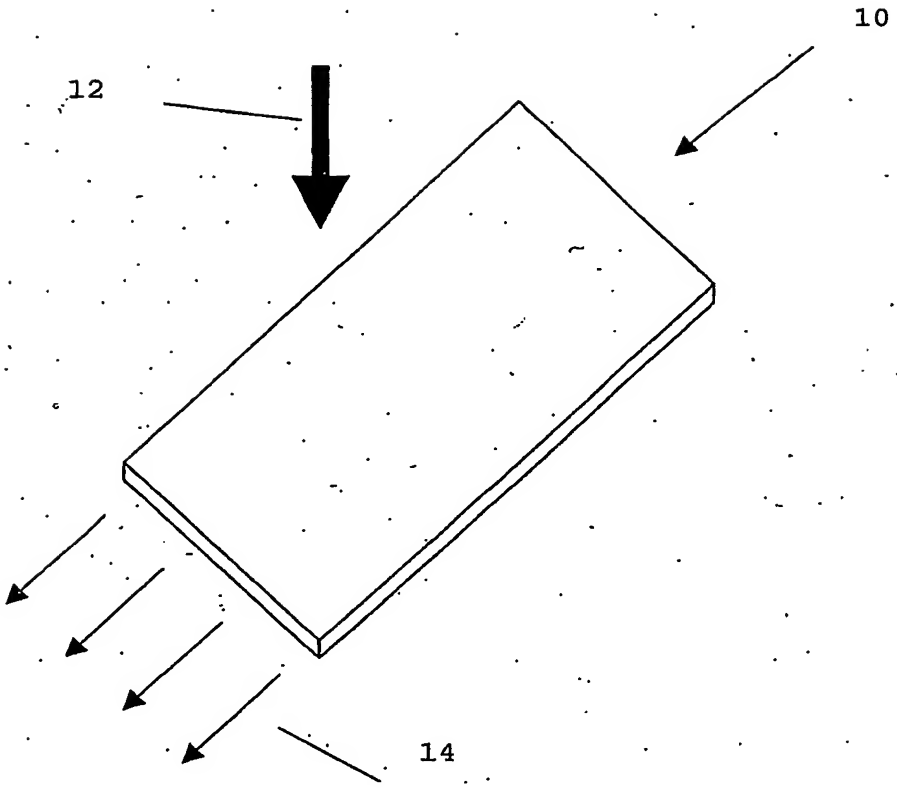

Figure 1

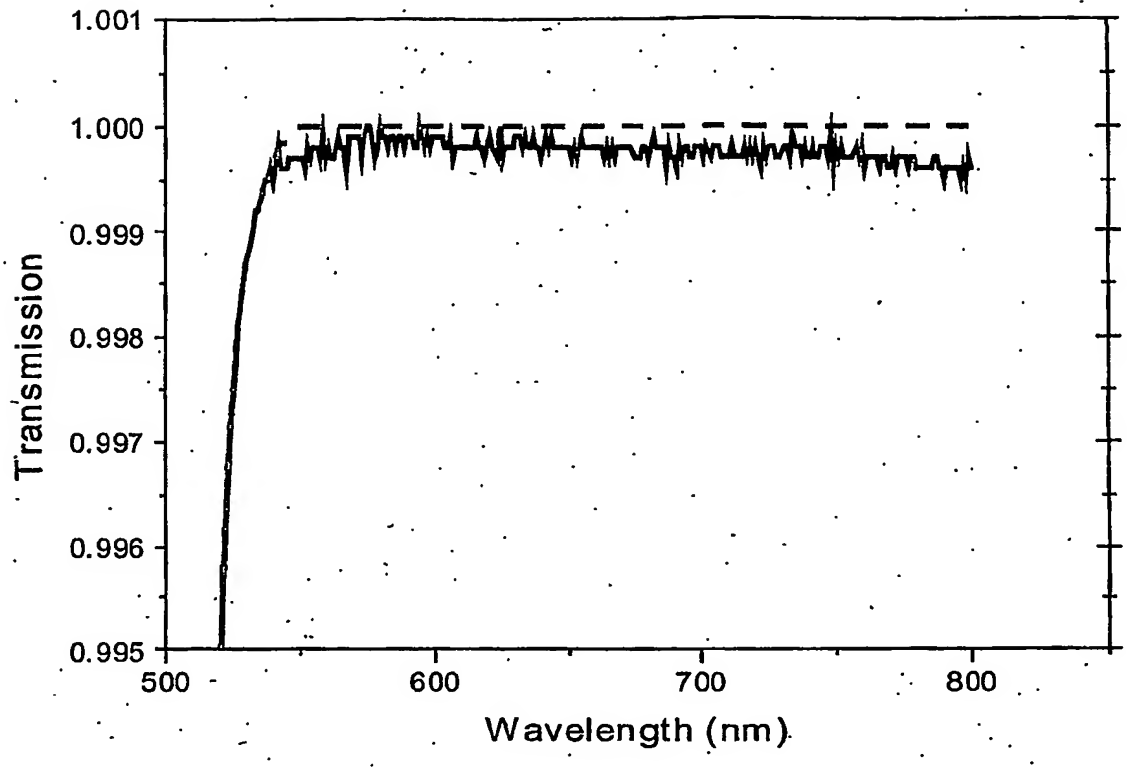

Figure 2